ARM Single-Column Modeling

The Next Five Years

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1. Introduction

Single-Column Modeling is one of the key strategies through which the U.S. Department of Energy's Atmospheric Measurement Program (ARM) aims to use data collected in the field to evaluate and improve models used for climate simulation. The purpose of this document is to provide a brief summary of what has been accomplished to date and, especially, to map out a strategy for continuing Single Column Modeling (SCM) work within the ARM Program in the years to come. We summarize the current thinking of the ARM SCM Working Group (WG) with respect to the accomplishments of the group to date, the near-term (order 1-year) plans of the group, and the longer term directions that ARM SCM research should take. The audience for this document includes:

- the ARM Management Team
- the other ARM WGs which interact with the SCM WG
- the remainder of the ARM Science Team, and finally
- the outside scientific community, including scientists participating in such programs as GCSS[1] and FIRE[2].

Section 2 gives relevant background, based primarily on the ARM Science Plan. Section 3 summarizes the methods that are used in SCM research, and the metrics which can be used to evaluate the utility and success of such research. Section 4 is a summary of ARM SCM activity through 1998. Section 5 describes completed and future field activity in support of SCM research. Section 6 discusses new methods envisioned for future SCM research. Section 7 provides a summary of the concepts used in SCM research and a proposed shift in emphasis towards parameterization development and testing. Section 8 gives our conclusions and recommendations.

2. A brief review of ARM's SCM strategy for testing cloud and radiation parameterizations

The primary scientific questions being addressed by ARM are as follows:

1. What are the direct effects of temperature and atmospheric constituents, particularly clouds, water vapor and aerosols on the radiative flow of energy through the atmosphere and across the Earth's surface?

2. What is the nature of the variability of radiation and the radiative properties of the atmosphere on climatically relevant space and time scales?

3. How can we quantify the relative importance of and interactions among the various dynamic, thermodynamic, and radiative processes that determine the radiative properties of an atmospheric column and the underlying surface?

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1. GCSS is the GEWEX Cloud Systems Study; GEWEX is the Global Energy and Water Experiment.
2. FIRE is the First ISCCP Regional Experiment; ISCCP is the International Satellite Cloud Climatology Program.

4. How do radiative processes interact with dynamical and hydrologic processes to produce cloud feedbacks that regulate climate change?

Models embody our ability to answer questions 1 and 3, and they are the tools with which we try to predict and/or simulate the answers to questions 2 and 4. Model development for ARM can be viewed as the process of advancing our understanding, and then encoding these advances in models. A key objective of ARM is to evaluate the successes and failures of the models, by systematic comparison of model results with ARM data. The radiative and cloud processes of particular interest to ARM are represented by physical parameterizations, which are key elements of the general circulation models (GCMs) used to simulate climate and climate change.

One approach to the use of ARM data for developing and testing cloud formation parameterizations involves the use of SCMs. As the name suggests, an SCM represents a grid column of a climate model, considered in isolation from the rest of the model. The basic idea is to measure the external forcing at work on a column of the atmosphere that corresponds to a single GCM grid column, to use models to compute the cloud formation and radiative transfer processes inside the column, and to evaluate the results produced by the models through comparisons with additional observations. The data required for use with an SCM include observed vertical profiles of temperature, water vapor, and condensed water, as well as the large-scale vertical motion and the tendencies of temperature, water vapor, and condensed water due to horizontal advection.

The SCMs are supplemented with more detailed models, which can be called cloud system models (CSMs). A CSM explicitly simulates cloud-scale motions, while parameterizing the smaller-scale turbulent motions. CSMs are designed to simulate the cloud-scale processes that must be parameterized in a GCM or SCM. A CSM domain may be considered to represent a GCM grid column, so that in a sense a CSM can be considered to be a detailed SCM. A CSM typically includes a turbulence parameterization, a bulk ice-phase microphysics parameterization, a cloud microphysics parameterization, and interactive solar and infrared radiation parameterizations. As with an SCM, observed large-scale vertical motion, horizontal advection, and horizontal pressure gradients can be prescribed as forcing functions. The observations of large-scale fields and tendencies required for scientific applications of a CSM are the same as those required by an SCM, and with the exception of the advective tendencies of condensed water these observations can be provided by ARM measurements. CSMs compute some things that are very difficult to observe, such as the vertical distributions of liquid water and ice. This simulated information is no substitute for real observations, because as mentioned above the CSMs do contain parameterizations, notably microphysics and turbulence parameterizations, which introduce major uncertainties. Nevertheless CSM results can be judiciously compared with SCM results in order to diagnose problems with the latter.

It is possible to use either a CSM or an SCM to develop or test a parameterization, and it is advantageous to use both. An approach involving both is illustrated in Fig. 1. All information flows from the field data, which are used to drive the SCM and CSM, and also to evaluate the model results. The results produced by the CSM can also be compared with those produced by the SCM. Finally, the parameterization tested in the SCM can be transferred directly to a three-dimensional GCM.

Up to now, almost without exception, evaluations of cloud parameterizations have relied upon comparison of simulated and observed climatological (usually monthly) means of the earth radiation budget or liquid water path. Comparison on shorter time scales has seldom been attempted The SCM has

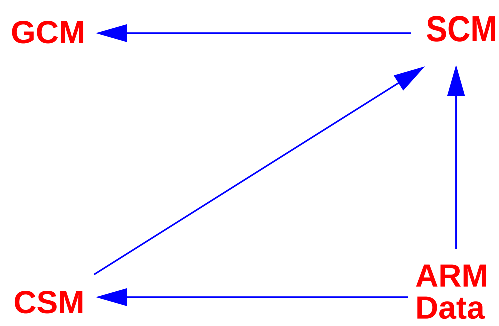

Figure 1. **Diagram illustrating how a CSM and an SCM can be combined with ARM data to develop improved parameterizations for GCMs. The arrows in the figure show the "flow of information." This flow starts with the ARM data, in the lower right-hand corner of the figure. The observations collected during ARM are used with both the CSM and the SCM, in essentially the same three ways for both models. First, both models are initialized from observations. Second, both are "driven" with the observations of, for example, large-scale vertical motion. Finally, the results that the two models produce, in response to this observed forcing, are compared against other observations collected in ARM, e.g. observations of cloudiness and surface radiation. Through data assimilation, ARM data also can be directly used by GCMs, although that is not part of the SCM approach.**

been selected by ARM as a useful testbed for cloud parameterizations (Randall et al., 1996 a), but as explained below providing the necessary lateral boundary conditions has proven to be extremely challenging, largely because of sampling and measurement errors in the winds (Zhang and Lin, 1997; Mace and Ackerman, 1996; Randall et al., 1996 a) and because of the lack of cloud measurements along the lateral boundaries (Petch and Dudhia, 1998).

3. SCM methods and metrics

As a postscript to the preceding somewhat philosophical discussion, it is useful to summarize, in practical terms, how SCMs and CSMs are being used to achieve progress towards ARM's scientific goals, and how we can measure the rate of such progress.

3.1 What SCMs can do

As discussed above, the key utility of SCMs is that they can be used to make connections between GCMs and data collected in the field, thus facilitating observationally based evaluations of new and supposedly improved parameterizations, in isolation from the large-scale dynamical framework of a GCM. The importance of such model-data connections can hardly be exaggerated. They are fundamental to the success of ARM, just as they are to the success of any other scientific endeavor.

In one particularly useful approach, multiple SCMs are applied to ARM-based case studies, so that the ensemble of model results can be *intercompared* among the models and with the ARM data. As discussed later in this document, ARM's SCM WG has organized one such intercomparison already, and two more are already planned. Intercomparisons of this type are useful in part because they help to bring the modeling community to the table. Participation tends to be strong for several reasons:

- Participants can take advantage of the data preparation carried out by the intercomparison team.
- The intercomparison case represents a standard or benchmark which can be used to perform an evaluation of the performance of a model relative to other models of the same type; and

- there is a perception that failure to participate in such intercomparisons “looks bad.”

In a second approach, SCMs can be used to isolate particular physical processes, allowing the effects of other processes to be prescribed for purposes of numerical experimentation. Examples are given by Randall et al. (1996 a).

Finally, SCM studies can suggest ideas which can then be developed and evaluated through theoretical work and/or observational studies.

3.2 What are the ingredients of a successful SCM study?

The most obvious prerequisite for a successful SCM study is the availability of an SCM. Over the past several years we have seen the creation of SCMs in many if not most of the global modeling centers around the world. NCAR[3] has begun giving an SCM away, complete with a graphical user interface. ARM can take a portion of the credit for this development, although GCSS and other field programs such as FIRE have also spurred SCM development.

In order to perform an SCM study, suitable data are needed. ARM and other field experiments are providing such data; in the case of ARM, the SCM Intensive Observation Periods (IOPs) are the key to making this possible. SCM IOPs are distinguished mainly by 3-hourly sonde launches from the central and boundary facilities. These frequent sonde launches permit analysis of the weather systems moving across the ARM Southern Great Plains (SGP) site with sufficient spatial and temporal resolution to capture the large-scale patterns. The analyses are then used to drive the SCMs and CSMs.

Even after the data have been collected, a strategy is needed for forcing the model with the data. The ARM SCM WG has devoted considerable time and energy to this issue. The task of *data integration* is absolutely key to the success of ARM, and it is a task which is always in danger of getting lost. Data integration consists of bringing together data from disparate instruments, and combining these data into a coherent physical description of what was observed, in a form suitable for use in the evaluation of the relevant models. A climate modeler cannot make use of raw radiometer data, or raw lidar data, or raw cloud radar data, or raw satellite data, or raw sonde data, or raw profiler data, or raw aircraft data. The modeler lacks the expertise to analyze such data, and, in any case, such an analysis is a full time job, which if undertaken by the modeler would preclude him or her from doing any modeling. Examples of analyses performed to date include the master’s theses of Rob Levy (CSU[4]) and Jason Burks (University of Utah). Fortunately ARM has set up the machinery needed to do data integration, within the WGs on Clouds, IRF, and, yes, Single Column Modeling. Nevertheless it is fair to say that the task of data integration is unfinished and that a *comprehensive* physical description of even one SCM IOP has yet to be produced by the ARM Science Team and ARM Infrastructure.

Perhaps most important of all, a good SCM study needs an idea worth testing. No one should imagine that simply running SCMs with ARM data somehow solves our scientific problems. The solutions to our problems come in the form of ideas. SCMs cannot in themselves have ideas. The models and the calculations performed with the models cannot free us from the need to generate new ideas about nature by thinking. The development of new parameterizations is typically done with a pencil and paper, during

3. The National Center for Atmospheric Research, which is sponsored by the National Science Foundation.
4. Colorado State University

precious and increasingly rare quiet moments of contemplation. Thinking will never be obsolete.

3.3 *What does a useful SCM result look like?*

An exemplary SCM study is one in which one of the following two possibilities applies:

- A promising new idea (e.g. a cloud formation parameterization) is subjected to tests with ARM data, using an SCM, and is then adopted for use in an important climate model or a numerical weather prediction (NWP) model.

- Observed but previously unexplained cloud processes are reproduced using an SCM or CSM. Diagnosis of the model results then provides a pathway to understanding the processes in question. This type of study does not necessarily make use of ARM data, although it may do so.

It follows that the SCM WG should be subjecting new parameterizations to tests with ARM data, using an SCM. This is happening, as a number of GCM groups, including ECMWF[5], NCAR, GFDL[6], GISS[7], PNNL[8], Scripps[9], and CSU have been using ARM data to evaluate their parameterizations. Some key results to date are as follows:

- In collaboration with J. Hack and the NCAR CCM SCM group, Xie and Zhang at SUNY[10] Stony Brook used ARM data to analyze the cause of a warm bias in the CCM3 SCM simulation of the July 1995 IOP climate at the ARM SGP site. They found that the temperature becomes anomalously cold when the CCM3 deep convection scheme is replaced by the moist-adjustment scheme or the Kuo scheme. They analyzed the triggering condition of convection in CCM3 and in the ARM data, and showed that convection occurs too frequently in the model. They also found that the diurnal variation of insolation over land produces large convective potential energy (CAPE) during daytime and minimum CAPE during nighttime both in the ARM data and in the model. As a result, convection is always triggered in the model during daytime when there is positive CAPE, while it does not always occur in the observations. Based on these results, Xie and Zhang proposed a simple modification to the triggering condition of convection in CCM3, and significant improvements were obtained in SCM temperature simulations (Xie and Zhang, 1998). Their study suggests a need to treat the triggering of convection over land differently from that over the tropical oceans.

- Ghan et al. (1998) have used ARM SGP observations to evaluate the same physics package in an SCM, a regional circulation model, and a global circulation model (with winds nudged

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5. The European Centre for Medium Range Weather Forecasts.
6. The Geophysical Fluid Dynamics Laboratory, which is operated by the National Oceanic and Atmospheric Administration.
7. The Goddard Institute for Space Studies, which is operated by the National Aeronautics and Space Administration.
8. The Pacific Northwest National Laboratory.
9. The Scripps Oceanographic Institution, which is operated by the University of California.
10. The State University of New York.

towards ECMWF analysis), and have identified consistent biases in the column water vapor, outgoing longwave radiation, and surface fluxes of sensible and latent heat.

We should also be endeavoring to understand observed but previously unexplained cloud processes through the use of SCMs and CSMs. Some key results to date are as follows:

- Xu and Randall (1995) used a CSM to investigate the mechanisms responsible for the observed diurnal cycle of precipitation over the oceans.

- Altocumulus is a thin, mid-level, stratiform, liquid water cloud. Numerical simulations of idealized nocturnal and diurnal altocumulus (Ac) layers have been carried out with the University of Utah CSM. In the nocturnal case, feedbacks between the liquid water path (LWP), infrared (IR) radiation, and entrainment lead to an Ac layer with a nearly steady structure and circulation. In the diurnal case, solar radiation leads to decreases in the LWP, circulation intensity, and entrainment rate relative to the nocturnal case. In addition, solar radiative heating in the cloud layer.

3.4 SCM-based studies as part of a well-rounded research strategy

SCMs cannot reveal the interactions of parameterized processes with the large-scale dynamics, simply because the large-scale dynamical processes are prescribed. This is an important limitation of the SCM strategy. The implication is that, regardless of what may be learned through SCM studies, parameterizations must still be tested in full climate simulations. Tentative “improvements” in parameterizations resulting from SCM research must subsequently be tested in simulations with the parent GCM and the effect of the parameterization change on some important aspect of climate variability or climate change documented.

Whenever possible, parameterizations should also be tested through NWP. Operational NWP provides excellent opportunities for comparing model results with data, which have not yet been utilized by ARM. There is now an ongoing collaboration between Jay Mace (ARM) and Christian Jakob (ECMWF) that has so far resulted in a comparison of model results and ARM data as summarized on J. Mace’s homepage at www.met.utah.edu.

This should be remedied in the future, by fostering collaborations with NCEP (the National Centers for Environmental Prediction) and ECMWF. Further discussion of this approach is given later.

4. A Summary of ARM SCM Activity Through 1998

The ARM SCM strategy has been implemented by carrying out a sequence of tasks which are just now reaching fruition. These tasks are listed in Table 1, with a “score” on a scale of 1 (just starting) to 5 (completed), indicating the extent to which each task has been accomplished to date. Further information is provided in the text below. This work has been documented through a series of SCM WG meetings and SCM Breakout Sessions at ARM Science Team meetings. Summaries of these meetings are provided in the Appendices of this document.

The penultimate task listed in Table 1, i.e. “Evaluate the model results,” is of course the point of the whole exercise. When the model results disagree with the observations, this is good news: it means that we have an opportunity to learn something. The learning process is rarely easy, however, because we must

Task	Score	Comments
Define the observational requirements for SCM-based ARM research.	3	We are still struggling with the advective tendencies of condensed water. The other quantities are in good shape for the SGP site, but we are working to define the best strategies for obtaining these quantities for the Tropical Western Pacific (TWP and North Slope of Alaska/Adjacent Arctic Ocean (NSA/AAO) sites.
Organize SCM IOPs designed to satisfy these requirements.	3	Successful IOPs have been carried out at the SGP site, but not yet at the TWP and NSA/ AAO sites.
Analyze the observations in such a way as to derive the required quantities.	3	Variationally constrained objective analysis is providing very useful data products for the SGP site at this time. We still lack adequate analyses of cloudiness and related fields. We are working with the ARM Cloud WG to resolve this. ECMWF analyses have been used for the Surface Heat Budget of th e Arctic (SHEBA) ship. ECMWF analyses are currently being tested for the TWP site.
Devise strategies for forcing SCMs with the data.	4	We have tested several strategies for forcing the models with data, and have identified the strengths and weaknesses of each.
Bring into the ARM research arena a diverse group of modelers with SCMs and CSMs capable of making use of the data.	4	The ARM SCM WG has participants from several of the major global modeling centers as well as other institutions.
Organize case studies which are then attacked by the modelers, in an intercomparison mode.	3	Our first intercomparison has been successfully carried out and the results are being written up for publication. Additional intercomparisons are planned.
Evaluate the model results.	3	The intercomparison has revealed strengths and weaknesses of the various models used.
Generate and evaluate new parameterizations	3	New parameterizations are being developed by members of the WG, but the WG itself has not devoted much time to this activity yet.

Table 1: Tasks being undertaken by the SCM WG. The “Score” represents the extent to which success has been achieved to date, on a scale of 1 to 5.

work to attribute the errors in the model results to some combination of:

- errors in the forcing data
- errors in the data for evaluation, and of course
- the particularly interesting errors in the models themselves.

Isolating the errors in the models is our most important goal. Disentangling the model errors from the errors in the data is a particularly thorny problem in the use of SCMs and CSMs, but in fairness the same or closely analogous problems arise in any comparison of models with data.

4.1 SCM IOPs

Table 2 lists the SCM IOPs conducted to date.

IOP Dates	Number of days	Weather Conditions	Comments
25 Oct - 13 Nov 1994	20	Precipitation fairly cyclic, falling every 3-4 days, with intensity tapering off through IOP.	First SCM IOP for which the profiler winds were available.
20 Apr - 7 May 1995	18	Several days of light rain, with some heavier rain showers near the end of the IOP.	Remote Cloud Sensing IOP VORTEX-ARM flights. Here VORTEX is the Verification of the Origins of Rotation in Tornadoes Experiment.
18 Jul - 4 Aug 1995	18	Frequent moderate showers in first half of IOP, then 5 dry days, and then more rain at end of IOP.	First ARM SCM Intercomparison case.
23 Sep - 20 Oct 1995	28	A few light to moderate rain events during the first weeks, then dry for 2nd 2 weeks of IOP.	Atmospheric Radiation Measurement (ARM) Enhanced Shortwave Experiment (ARESE) .
16 Apr - 5 May 1996	20	3 main rain events, spaced about every 6 days, with heaviest event in middle of IOP.	ARM UAV and NASA (National Aeronautics and Space Administration) SUCCESS (Subsonic Aircraft: Contrail and Cloud Effects Special Study) programs.
16 Jul - 4 Aug 1996	20	Light shower during the first 6 days, then light-to-moderate showers every other day for remainder of IOP.	BLX96 boundary layer flights.
3 Apr - 22 Apr 1997	20	Variably cloudy and cool, with overcast, rain/fog/snow during the first half, clearing later in the IOP.	Cloud Radar / Aerosol IOPs.

Table 2: A summary of the dates and durations of the ARM IOPs, and a sketch of the weather conditions encountered.

19 Jun - 18 Jul 1997	30	Frequent deep convection with associated upper-level stratiform clouds; some clear days in the middle of the IOP; 9 rain events, with the heaviest at end of IOP.	Second ARM SCM Intercomparison case, to be performed jointly with GCSS WG 4. GCSS WG 1 is also interested in this case.
16 Sep - 5 Oct 1997	20	Variable cloudiness during first week, followed by increasing clouds and moderate rain from remains of Hurricane Nora; last 10 days were mostly clear.	Integrated IOP; SCM IOP integrated with five other simultaneous IOPs. Second ARM SCM Intercomparison.
20 Jan - 8 Feb 1998	20	Mostly clear and cool to cold conditions; occasional overcast at mid and high levels, and low overcast and fog.	First true winter SCM IOP
28 Apr - 18 May 1998	20	Wide-ranging conditions, including cold rain, severe thunderstorms, and clear and hot; majority of the IOP was clear.	Cloud IOP (cirrus retrieval).

Table 2: A summary of the dates and durations of the ARM IOPs, and a sketch of the weather conditions encountered.

4.2 Objective analysis

Among the data needed for modeling studies that deal with cloud formation processes are time varying vertical profiles of the large-scale vertical motion and the tendencies of temperature and moisture due to horizontal advection. These are, of course, particularly troublesome quantities to observe, and in fact they can only be obtained by very indirect means, which have been developed to overcome problems with missing data, instrument errors, and incomplete spatial and temporal coverage. Broadly speaking, there are two approaches. First, objective analysis methods can be used to combine measurements from various sources (e.g. radiosonde data, wind profilers, etc.) in order to obtain synoptic descriptions of the large-scale dynamical and thermodynamic fields. These can then be differentiated (typically by approximate numerical methods) to infer such quantities as wind divergence and horizontal temperature and moisture gradients.

Estimates of dynamical and thermodynamical fields based on objective analysis (without a first guess provided by a model) are independent of physical parameterizations, which is a highly desirable feature. Some preliminary studies suggest, however, that the errors associated with objective analysis are sometimes too large to meet the stringent SCM measurement requirements. The errors are likely to be particularly large in data-sparse regions such as the Tropical West Pacific (TWP) and North Slope of Alaska/Adjacent Arctic Ocean (NSA/AAO) or for variables either poorly sampled or subject to large measurement errors (i.e., water vapor, microphysical parameters, and vertical motion).

The technique employed by the Lawrence Livermore National Laboratory (LLNL) for the objective analysis is based on that originally proposed by Barnes (1964) and subsequently used and documented by many others. Caracena's (1987) formulation is used to obtain the spatial derivatives. For application at the SGP site, the temperature and moisture observations from radiosondes at approximately 10-m vertical resolution are processed into 10 hPa layers from 960 hPa to 100 hPa for each of the five simultaneous soundings. Wind observations from the soundings are merged with those from neighboring NWS wind profilers to provide wind fields for the 10 hPa layers.

Objective analyses are then performed on these layer-averaged data to provide values of site-wide means and spatial derivatives. Values of winds and spatial derivatives are used to estimate advective tendencies of temperature and moisture. Divergence of the horizontal wind for each layer are integrated, applying O'Brien's (1970) correction, to obtain estimates of large-scale vertical motion.

Improvements have been made in the LLNL objective analysis scheme that address issues of spatial and temporal representativeness. The incorporation of large-scale analyses via the NCEP Rapid Update Cycle (RUC) model output reduce extreme values of the spatial gradients. Similarly, time-filtering the input data streams results in better-behaved SCM forcing fields.

4.3 Variational enhancement of the objective analysis

As demonstrated by Zhang and Lin (1997), variational methods can be used to impose constraints such as conservation of dry air mass, conservation of water mass, conservation of total energy, and conservation of momentum. The use of these constraints can yield major improvements in the objectively analyzed fields.

In this method, a variety of surface and top-of-the-atmosphere (TOA) measurements of water and energy fluxes, in particular precipitation measurements from dozens of Oklahoma Mesonet stations, are used to constrain the accuracy of grid-scale vertical velocity and advective tendencies. The constrained product guarantees that what comes in from the lateral boundaries of an atmospheric column equals to what comes out at the top and bottom plus the local change. This is achieved through a variational technique using minimum possible adjustments to the original sounding and profiler data subject to the constraint requirements.

We find that the adjustments made in the variational analysis to the atmospheric state variables are comparable in magnitude to the corresponding measurement uncertainties: for about 95% of the grid cells, wind adjustments are less than 1 m s^{-1}, temperature adjustments are less than 0.6 K, and below 850 mb moisture adjustments are less than 0.4 g kg^{-1}. Despite their small magnitudes, these adjustments can greatly impact the analysis of vertical velocity and advective tendencies. For example, a systematic wind error of 0.5 m s^{-1} for an array of 1000 km size can result in a very serious error of 3 mb $hour^{-1}$ in the grid-scale vertical velocity. Without any adjustments to the sounding data, spurious residual sources and sinks in the column budgets of water vapor and energy can have the same magnitudes as other leading components.

Since the concept of this variational method is based on physical principles using supplemental measurements, rather than through subjective tuning, the method is less sensitive than the conventional methods to the processing of the raw data. It also has the potential to incorporate other measurements which can be used to formulate additional constraints. The constrained product becomes an integrated data set from dozens of ARM measurement platforms that can be used beyond SCM activities.

Work to date suggests that the variational constraints significantly improve the analysis over what is possible without it.

4.4 First SCM SGP Intercomparison Case

We have begun a series of SCM Intercomparison case studies to evaluate the adequacy of the forcing data sets and the progress of SCM formulations. The first case study addresses the prescription of advective forcing, the methods used to derive SCM forcing terms, and the methods used to estimate surface flux forcing. The first case study is based on data from the Summer 1995 SCM IOP, where a range of weather conditions occurred, including local convection and weak synoptic forcing with varying intensity of precipitation, and clear-sky conditions. There are nine participating modeling groups, which include eight SCMs: Ghan (PNNL), Randall/Cripe (CSU), Somerville/Iacobellis (Scripps/UCSD[11]), Klein (NOAA[12]/GFDL[13]), Lohmann (Dalhousie), Stenchikov/Robock (Maryland, Rutgers), Zhang/Xie (SUNY Stony Brook), Sud/Walker (NASA/GSFC[14]), and one two-dimensional (2-D) cloud-resolving model: Xu (CSU). Details of the SCM Intercomparison procedures are given elsewhere (Cederwall, et al., 1998).

Three methods for prescribing the advective forcing were tested: (1) observed total advective tendency, (2) observed horizontal advective tendency plus vertical advective tendency estimated using observed large-scale vertical motion and the model-predicted vertical gradient, and (3) horizontal advective tendency estimated using a relaxation toward upstream values, plus vertical advective tendency estimated as in (2). SCM advective tendency terms were obtained in two ways: (a) Barnes objective analysis using ARM sounding and NOAA wind profiler data; and (b) variational analysis (provided by Zhang) that uses additional data to adjust the advective tendencies in order to match the observed column-integrated tendencies of mass, moisture, static energy, and momentum (Zhang and Lin, 1997). Surface forcing was prescribed from two methods of heat and moisture flux estimates: (i) area-averaged observations from Energy Balance Bowen Ratio (EBBR) stations, and (ii) area-averaged SiB2 model output (from a 6.25-km grid) that uses ARM observations as input (Doran, et al., 1998). Comparisons between simulated and observed values were made for such quantities as temperature and moisture profiles, surface and TOA radiative fluxes, column-integrated cloud-liquid water, precipitable water, and rainfall rate.

Based on the preliminary analyses for the Case 1 simulations, we have drawn the following, preliminary conclusions:

- Simulations are more realistic with forcing terms derived by the variational analysis.
- Simulations match observations better for clear-sky conditions than for cloudy conditions.
- The relaxation toward upstream values is the preferred prescription for advective tendency when evaluating process parameterizations, especially those for clouds.
- In general, the CSM performs better than the SCMs.

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11. University of California at San Diego
12. National Oceanic and Atmospheric Administration
13. Geophysical Fluid Dynamics Laboratory
14. Goddard Space Flight Center

The results were mixed for simulations using the two different estimates of surface forcing. This is under further study by a subgroup of participants.

4.5 SCM outreach through 1998

SCM outreach activities through 1998 included interactions with the Cloud WG, the Instantaneous Radiative Fluxes (IRF) WG, and GCSS

4.5.1 Interactions with the Cloud WG

Through the SCM WG's liaison with Steven Krueger, who is the Co-Chair (with Jay Mace) of the ARM Cloud WG and also an active member of the ARM SCM WG, the ARM SCM WG is cooperating with the ARM Cloud WG to develop a set of cloudiness data products suitable for use with SCMs current issues are as follows:

- *Millimeter cloud radar (MMCR) retrievals.* The MMCR retrievals will eventually provide profiles of cloud fraction, cloud water content, and cloud ice content. Especially important is cloud characterization during IOPs. Rapid progress is being made on retrievals for pure liquid and pure ice clouds. Mixed-phase clouds remain a challenge. Contamination of echoes by insects is a serious problem at the SGP site during the warmer months of the year. Calibration issues also exist, but should be worked out soon.

- *Cloud cover.* The Whole Sky Imager (WSI) is capable of providing the fraction of thin and thick cloud covering the whole sky. Delays in providing this data have been primarily due to a lack of communication between the WSI developers/data processors and the end users. Cloud fractions obtained from the WSI and from Minnis' satellite cloud products have been compared with cloud fraction derived from the time series of micro-pulse lidar (MPL) cloud detections. It was found that the WSI is not detecting thin clouds, especially thin high clouds and that the Minnis cloud fraction is systematically larger than that derived from the MPL, especially during partly cloudy conditions. A tentative conclusion is that this difference is due to the threshold technique used by Minnis.

4.5.2 Interactions with the IRF WG

The SCM group as currently constituted has little atmospheric radiation expertise. There is a clear need for ARM scientists in this area to join the SCM effort by running new candidate radiation codes in SCMs. Furthermore, there is a need for ARM to begin routinely producing cloud radiative property parameters (optical thickness, albedo, emissivity) that are the links between the hydrologic variables predicted by cloud parameterizations and the radiative fluxes they affect.

Accordingly the SCM WG and the IRF WG have begun to increase their level of interaction. A focus of the IRF/Cloud/SCM interactions will be radiation parameterizations, spanning issues from water vapor and cloud effects to the testing of cloud and radiation parameterizations in SCMs. The SCM WG will also work with the IRF Atmospheric State Steering Committee on requirements and prospects for characterizing the atmospheric column with retrievals from remote-sensing, as a supplement to the radiosondes (which the SCM WG now relies on exclusively for deriving SCM forcing terms). The SCM and IRF WGs are planning to run radiation codes in GCMs, SCMs, and NWP models to calculate the direct beam and compare this with ARM data.

4.5.3 Interactions with GCSS

GCSS has adopted SCMs and CSMs as key elements of its strategy to improve cloud parameterizations in the GCMs of the world's climate modeling and NWP communities. The ARM SCM WG has established a joint project with GCSS WG 4, in which both groups will use ARM SGP data for a case study. It also appears likely that GCSS WG 1 will develop a case study based on the same SCM IOP. These developments mark an important use of ARM data in the international scientific arena. The joint ARM-GCSS case study is being planned in the latter half of 1998, and will be carried out in 1999.

GCSS WG 4 recently completed two projects designed to evaluate CSMs and SCMs using TOGA (Tropical Ocean and Global Atmosphere) COARE (Coupled Ocean Atmosphere Response Experiment) datasets. Case 1 involved SCM and CSM simulations of a squall line lifecycle for a period of several hours. Case 2 involved SCM and CSM simulations of the evolution of deep convection over the Intensive Flux Array (IFA) modulated by observed, time-dependent, large-scale forcing for a period of 6 days.

Two-dimensional and three-dimensional (3-D) simulations were performed for Case 1 with seven different CSMs. Sensitivity tests to microphysical parameterization, surface fluxes, radiation, domain size and dimensionality of domain (i.e., 2-D vs. 3-D) were made. Three SCMs were used, and one tested four different cumulus parameterization schemes. Overall, cloud-resolving models are able to simulate the gross observed features of the squall line (e.g., mean precipitation structure and speed of propagation). Ice parameterization seems necessary for a significant development of the stratiform region.

Case 2 was used to evaluate CSM and SCMs by testing their ability to determine the large-scale (domain and time-averaged) statistics of precipitating convective cloud systems during a multiday period. The participating models included seven 2-D CSM, one 3-D CSM, and seven SCMs. The models have been evaluated by comparing the results of the simulations to observed large-scale (average) quantities. The similarities between the results from the CSMs and the observations for tropospheric enthalpy, precipitable water, outgoing longwave radiation (OLR), and cloud (liquid plus ice) water path, among others, suggest that the bulk characteristics of convection are determined (in a diagnostic sense) by the large-scale thermodynamic advective tendencies, and suggests that CSMs are useful tools for performing this diagnosis. Systematic differences that occurred between the SCM and CSM results for several quantities suggests that the CSM results should be useful for improving the SCMs.

All models developed a cold bias of about 2 K, with a similar evolution. This is believed to be largely due to errors in the imposed large-scale forcing. This conclusion was reached after careful analysis of the tropospheric budget of moist static energy over the IFA (e.g., Emanuel 1998; Burks 1998). This emphasizes the need for large-scale analyses that have been constrained by large-scale budget requirements.

5. Completed and Future IOPs

ARM has been and is conducting SCM IOPs at the rate of several per year. We now explore how these data have been and will be used.

5.1 Detailed analyses of IOPs already conducted

5.1.1 July 1997 IOP

The June-July 1997 SCM IOP provided data on mid-latitude continental convection. It will form the basis for a model intercomparison case, which will be exciting for two reasons:

(1) The MMCR was operational during this time and data from it will be used to retrieve profiles of cloud properties.

(2) The case will be done in collaboration with the GCSS WG 4 (Precipitating Convective Cloud Systems). This will significantly increase the number of participating modelers, especially those running CSMs, and hence the visibility of this intercomparison case.

5.1.2 Fall 1997 Integrated IOP

The ARM Program's largest IOP to date was conducted from September 15 to October 5, 1997 at the SGP site. Most of the activity was focused at or near the Central Facility. Six separate but interrelated IOPs were conducted simultaneously: Water Vapor, Cloud, Aerosol, Shortwave Radiation, UAV, and SCM. The Central Facility served as the focal point for ground-based remote sensing instrumentation. Over 40 guest instruments were brought to the Central Facility. Five aircraft were flown: the North Dakota Citation and Wyoming King Air for the Cloud IOP, the PNNL G-1 Gulfstream for the Aerosol IOP, and the Altus UAV and Twin Otter chase plane. These aircraft provided an unprecedented in-situ sampling of radiation and atmospheric constituents in the column over the SGP Central Facility. These measurements provide a unique opportunity for validation of retrieval algorithms and parameterizations that eventually have application to the SCM research.

Unfortunately, these activities are limited to a narrow column above the Central Facility, and therefore do not have direct applicability for driving and validating SCMs. During the integrated IOP, we did obtain an excellent sampling of the site-wide column using radiosondes at 3-hour intervals. Across the five launch sites, 817 (out of the possible 825) soundings were launched. Of those, 799 (or 98%) ascended above an altitude of 10km.

5.2 Additional SCM IOPs

Currently five SCM IOPs are planned for FY99: three for the SGP, one for TWP (in conjunction with Nauru '99), and one for NSA/AAO.

5.2.1 SGP

It is likely that the SGP will remain the primary site for SCM IOPs, due to the wealth of data available, and the wide variety of meteorological conditions that occur. However, the NSA/AAO and TWP sites offer unique opportunities for SCM work due to meteorological and radiative conditions that cannot be duplicated at the SGP site. Therefore, we see these sites as important supplements to the SCM efforts with SGP data. Although we have not yet analyzed the SGP Winter 1998 SCM IOP data, we assume that it adequately captured winter conditions of interest to ARM. We strongly advise ARM to conduct two SGP IOPs in FY99, so that we can test the ability of ARM to provide retrievals of atmospheric profiles from remote-sensing (see discussion below), and hence reduce our dependence on high-frequency radiosondes and 3-week IOP scenarios. Possibly a shortened (10-day) IOP could be run in convective conditions to complement the more synoptically driven conditions of a March period at the SGP.

The requirement for in situ sampling by sondes and perhaps aircraft makes the collection of SCM data particularly expensive, and it also limits the applicability of the SCM strategy to places and times in which sondes and aircraft can be used. Great savings could be realized if sonde launches could be cut back. This would become possible if it could be demonstrated that most or all of the data needed for SCM IOPs can be obtained by remote sensing. It should also be noted that remote sensing products offer the advantages of high temporal resolution and, in some cases, improved spatial sampling relative to sondes. For these reasons, it would be wonderful if sonde data could be replaced by enhanced remote sensing products. This would be a boon not only to ARM, but to virtually all meteorological field programs, and also to data gathering in support of operational weather forecasting.

The SCM WG is, therefore, preparing to provide to the remote sensing scientists in ARM a list of sonde-based data products required for SCM research, along with estimates of the tolerable errors for each variable. We anticipate that the remote sensing team within ARM will attempt to supply these products for one or more SCM IOPs. We await the arrival of a prototype dataset for testing purposes. Sonde data will also be available for the same IOPs. This sonde data will be used for evaluation of the remote sensing products, and also to produce a parallel set of SCM forcing data by conventional methods. The SCM WG will then undertake a comparison of SCM results with and without sondes. This comparison exercise should be carried out for multiple IOPs at different times of year and under a variety of weather regimes.

The results of this exploratory study should form the basis for an evaluation of the feasibility of cutting back on sonde launches for SCM IOPs. Problems with initial and boundary conditions for SCMs and CSMs are the same at the NSA/AAO and TWP sites. Investigations into the supplementation of operational products through objective analysis or data assimilation needs are required to see if the SCM approach is feasible at these locations.

5.2.2 NSA/AAO

5.2.2.1 Interactions with FIRE and SHEBA during 1997 and 1998

FIRE, in collaboration with SHEBA and ARM, provided two one-month aircraft-supported IOPs during April-May and July 1998. At least two ARM modeling teams (at the University of Colorado and at CSU) have already run SCMs with the ECMWF analyses, which ingested SHEBA 2x daily radiosondes (and 4x daily during the IOPs). Can we improve on that success with the addition of ARM observations? An IOP will help answer that question, as will the SHEBA and FIRE campaigns. The NSA/AAO SCM IOP design and objectives may change based on what is learned from SHEBA and FIRE.

If a wide range of surface temperatures (say -8° C to -40° C) occurred during the NSA/AAO IOP, we would have a potentially ideal opportunity for testing the assumptions that cloud parameterizations make about when condensate is liquid and when it is ice, as a function of such parameters as temperature, dynamics, cloud age and vertical extent. For example, the UKMO[15] GCM parameterization goes from liquid to ice between 0° C and -15° C, while the GISS GCM parameterization does it from -4° C (ocean) or -10° C (land) to -40° C, with modifications of the normal temperature dependence when ice falls into supercooled water from above. ARM has the opportunity to resolve questions like this. This raises the question of what cloud measuring instruments are or will be out there. We would need a microwave radiometer (MWR) to detect any liquid, and other things sensitive to ice. It is not known whether the MMCR will be running at the NSA/AAO during the planned IOP.

15. United Kingdom Meteorological Office.

Certainly these cold conditions existed at the SHEBA ice camp, and thanks to ARM the required instrumentation was there, including an MWF and a cloud radar. In addition, FIRE conducted a total of 28 flights over the camp using an aircraft equipped with microphysical probes.

5.2.2.2 Future NSA/AAO IOPs

The SCM WG supports plans for a March 1999 SCM IOP. There are trade-offs to be considered (e.g. timing relative to SHEBA/FIRE-ACE (Arctic Cloud Experiment) and associated analyses, design of flight patterns, reliability of aerosondes in cold weather) which temper our enthusiasm.

The SCM WG notes that it is not solely or even primarily responsible for the planning and execution of SCM IOPs at the NSA/AAO (or anywhere else). The NSA/AAO Site Scientist has the ultimate responsibility for organizing and conducting NSA/AAO IOPs. Resources for such IOPs are allocated by the ARM Management Team in consultation with the ARM Science Team Executive Committee. The roles of the SCM WG are:

- to participate in the IOP planning process
- to conduct SCM studies
- to foster scientific use of the data by the global modeling community, both within the ARM Science Team and in the community at large.

SCM activities at NSA/AAO will use NWP models as a complementary source of “data” to characterize the column advective tendencies and mean state. Observations are quite limited, compared to the SGP site. The proposed NSA/AAO SCM IOP gives us the opportunity to evaluate how well the NWP products represent the atmospheric state, and to develop strategies that optimally use both NWP products and the available suite of NSA/AAO observations, especially upper air observations.

Although aerosondes will give us measurements similar to those obtained with radiosondes, the typical sounding obtained by a radiosonde will not be duplicated by an aerosonde. We expect that there will be radiosonde launches at Barrow at least twice per day; more frequent launches are desirable to provide profiles to integrate with the aerosonde data.

With the opportunity to test assumptions that cloud parameterizations make about when condensate is liquid and when it is ice, we need an MWR to detect any liquid, and other things sensitive to ice. The MMCR at Barrow will also be a valuable source of cloud characterization. For cirrus clouds, we are interested in what relative humidities are required for ice cloud formation, and what that tells us about whether nucleation is homogeneous or heterogeneous. We need a way to distinguish whether conditions are supersaturated with respect to ice but below water saturation, or at water saturation.

A polarization lidar similar to the ETL[16] unattended aerosol lidar (DABUL) will be available for the proposed NSA/AAO SCM IOP. The information from this instrument is *very* useful for distinguishing hydrometeor phase, and is available for SHEBA. We will also have a submillimeter radiometer which can provide water vapor profiles and ice water path.

16. Environmental Technology Laboratory

The proposed NSA/AAO SCM IOP offers us a chance to do simulations with some very cold clouds under conditions not dominated by advection (which is often the case for midlatitude cirrus). This would be a good test for the aerosondes. It is not clear whether there will be any in situ ice crystal sampling.

The reliability of the aerosondes in the extreme cold of the Arctic environment is not known but represents a potential difficulty. We will need to observe the spatial gradients of temperature, moisture, and winds. Vertical gradients can be sampled by sounding patterns (and the Barrow radiosonde). Horizontal gradients require multiple aerosondes (at least three) flying simultaneously, since one or two aerosonde making circuits is not going to be able to adequately sample the SCM domain at the 3-hourly interval (or even 6-hourly) that we desire for obtaining SCM forcing terms.

As always, a major concern is the stated accuracy of the winds, and the associated divergence error. The stated divergence error of 2×10^{-5} s^{-1} corresponds to an error in vertical velocity of 2 cm s^{-1} at 1000 m, given constant divergence and zero velocity at the surface. This accuracy is comparable to that which can be obtained with radiosondes. One purpose of vertical velocity measurements is to infer the entrainment velocity as a residual from the mass budget. Entrainment rates in radiatively active stratiform cloud layers are typically on the order 1 cm s^{-1}. Thus, the usefulness of the aerosondes for accurate divergence estimates is a bit doubtful, unless the strategy is changed (such as using a larger circle, or making optimum use of assimilation into operational NWP models). Have wind data from aerosondes been compared to that from a profiler network, in terms of accuracy, frequency, and areal coverage of winds? This question could be at least partially answered through testing aerosondes at the SGP, where such comparisons could readily be made.

Are there ways to reduce the effects of the divergence error during our analyses, e.g., by choice of flight patterns, use of NWP model output, and/or optimal merging with radiosonde data? Lenschow (1995) has considered these issues.

The selection of aerosonde flight patterns must be carefully considered. We seek to minimize the uncertainty in the horizontal gradients of temperature, moisture, and winds. With the fine layering observed in the Arctic, we also need to capture the vertical gradients as well as we can (the radiosondes will help characterize this fine vertical structure).

5.2.3 TWP IOPs

Use of SCM and CSM simulations is a powerful and direct method of testing parameterizations over the TWP. Given the sparsity of observations in the neighborhood of the Atmospheric Radiation and Cloud Station (ARCS), the use of operational analyses will be critical to provide initial and boundary conditions. Investigations are needed into the accuracy of these fields and whether the accuracy and resolution of these standard products could be improved using ARM data and data assimilation techniques.

5.2.4 Summary

Based on the considerations discussed above, we anticipate the following SCM IOPs during FY99:

- SGP, March 1999 (cool season stratus, not yet sampled in ARM)

- TWP -- Nauru '99 triangle pattern (6/23-6/28/99)
- NSA/AAO, March 1999 (proposed sampling with aerosondes)
- SGP, Winter 1999 (early January)
- SGP, convective period, to be conducted jointly with another IOP activity.

The first three of these are of comparable priority; the fourth and fifth are highly desirable but not critical.

6. New technical methods for future ARM SCM research

6.1 Analysis of advective tendency of condensed water

Clouds advecting into the SCM domain pose very significant problems, especially for cirrus clouds. The errors due to neglecting condensate advection could be at least as important as the errors present in the analyzed advective forcings of potential temperature and water vapor. ARM needs to find a way to measure the advective tendencies of condensed water variables. This might be achieved through use of multiple doppler cloud radars. ***The SCM WG wishes to flag this as an important observational issue for the ARM Program as a whole.*** It will certainly be an issue in any and all future programs focusing on large-scale cloudiness; if ARM can make progress towards solving the problem, it will benefit the whole community.

6.2 Regional modeling

We now discuss two alternatives to the SCM/CSM strategy. The first replaces the SCM with a regional model, thus extending the modeling domain so that it is large enough that the lateral boundary conditions for the cloud variables are unimportant for the smaller region; previous work by Westphal et al. (1996) indicates that a domain of at least 1000 km is necessary for strongly advected high cirrus clouds. Because this is much larger than the size of a single GCM grid cell, a multidimensional regional circulation model (RCM) is necessary for such a domain. By predicting the circulation within its domain, the circulation in an RCM is less sensitive to errors in the lateral boundary conditions than in an SCM because the model dynamics permit geostrophic adjustment. Moreover, by predicting the cloud variables throughout the model domain, the lateral boundary conditions for the clouds in the region are dependent upon the same treatment of cloud microphysics outside the region as within, thus eliminating inconsistencies between the treatment of clouds in an SCM and in a regional model providing its lateral boundaries.

One of the requirements of a cloud parameterization is that it represent the full life-cycle of clouds: their formation, persistence, and decay. For clouds forming under strongly advective conditions, the domain traversed by a cloud during its life cycle can be thousands of kilometers, much larger than that of an SCM or CSM. Evaluation of a cloud parameterization under such conditions can only be achieved by a model spanning a domain much larger than that of an SCM or CSM; otherwise the lateral boundary conditions for the cloud variables will control the simulation of the cloud. RCMs offer an alternate cloud modeling strategy that satisfies the need for a larger domain. The resolution of these models should be comparable to that of GCMs so that cloud parameterizations can be evaluated at the appropriate resolution. However, experience has shown that dynamical instabilities within the RCM domain can render simulations meaningless unless the simulation is constrained by data assimilation to follow the observed winds. Care must be exercised to ensure that the data assimilation procedure does not compromise the independent evaluation of the cloud parameterization. The estimates of these fields by objective analysis (without a first guess provided by a model) are independent of physical parameterizations, which is a highly desirable feature. However, preliminary studies have shown that the potential errors associated with objective analysis of data taken in the vicinity of the ARM site may be sometimes too large to meet the stringent measurement requirements of SCM modeling. The errors are likely to be unacceptably large in data-sparse regions such as the TWP or NSA/AAO, or for variables either poorly sampled or subject to large measurement errors (i.e., water vapor, microphysical parameters, and vertical motion).

6.3 NWP

The second alternate strategy is to constrain a GCM with observed temperatures, winds, humidities, etc., through global NWP with data assimilation (e.g. Jeuken et al., 1996). This means doing operational or quasi-operational NWP. We do not believe that it makes sense for ARM to get into the NWP business, for two reasons:

- Data assimilation is an extremely complex, arcane, and expensive process, which is far from the central goals of ARM.
- The operational centers are already performing such assimilations, and their products are available or can be made available to ARM through suitable arrangements.

Every day the operational centers perform multiple forecasts, at a variety of resolutions, using global models very similar to those used in climate research, and using cloud and radiation parameterizations, which are in some cases state-of-the-art. The data assimilated to provide the initial conditions for these forecasts include some ARM data, e.g. from the SGP, and additional ARM data can be included in the future. The results of the operational forecasts provide opportunities to evaluate the parameterizations used in the NWP models. In addition, the analyses produced through assimilation can be used as forcing for SCMs and CSM.

Data assimilation procedures have been developed to handle incomplete and redundant sets of diverse data and to provide a description of the atmosphere that is consistent with the underlying physics such as, for example, the balance between the dynamical and thermal structure. Multiple estimates of the same quantity can be reconciled in a way that takes into account the error characteristics of each data source. ARM should provide in real-time (via the WMO[17] Global Telecommunications System) any ARM special observations (i.e., sondes, surface observations, profilers) of use to the operational data assimilation and forecasting centers. In exchange, ARM should receive from the operational centers nonstandard (direct model output) as well as standard analyzed fields. In addition, ARM should supplement the operational data assimilation with its own local assimilation that includes assimilation of other data (e.g., surface fluxes and column cloud water, and precipitable water, which are not presently assimilated by operational models) into both high-resolution models that directly resolve deep convection, and regional models with resolution comparable to that of GCMs. The local assimilation can use four-dimensional assimilation, such as the adjoint technique, Kalman filters and Newtonian nudging, which take advantage of the relatively high temporal resolution of the measurements over the SGP.

Data sets produced by assimilation are only proxies for real data, because the physical

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[17]. World Meteorological Organization

parameterizations of the NWP model used do affect the results, particularly in data-sparse regions, and particularly in the tropics. Moreover, if the data assimilation procedure is optimized to maximize agreement with observed clouds, the independent evaluation of cloud parameterizations can be compromised. A modeler wishing to test cloud parameterization A may rightly feel very nervous about using assimilation products produced by an NWP model that employs cloud parameterization B.

Differences between the objective analysis and assimilation products have been used to diagnose shortcomings in parameterizations, as well as errors in the objective analysis. With these caveats in mind, assimilation products can be useful because they offer unmatched spatial coverage and comprehensive information about the dynamical and physical fields, and are the only viable alternative in data-sparse regions.

We recommend that ARM establish and/or strengthen its cooperative arrangements with existing operational NWP centers such as NCEP and ECMWF, in order to:

- ensure ongoing and close scrutiny of cloud and radiation forecasts for the ARM sites
- explore the use of assimilation products for forcing SCMs and CSMs.

6.4 *Standardized SCM forcing data format*

At present SCM work is going on at many centers around the world, but there is no standardized format for the forcing data used to drive an SCM. A format has been developed, at LLNL, for use by the ARM SCM WG. With suitable documentation this ARM-developed format might be suitable for adoption by the larger community. The SCM WG intends to pursue this possibility, in part through interactions with GCSS.

6.5 *Digital publication of IOP datasets*

As discussed above, we have now amassed a collection of analyzed ARM SCM IOP datasets. We have also been working with data collected by other programs, including GATE[18], FIRE, and TOGA/COARE. In addition to these observational analyses, we have SCM and CSM results produced through use of the data. These various products can be published, on the web and also via CD-ROM or DVD. The SCM WG intends to pursue this idea.

6.6 *Community SCMs and CEMs*

From the beginning of ARM, there has been a recognition that it might be useful to adopt specific models for possible use by ARM researchers. This does not mean that ARM researchers would be *required* to use these specific models; any ARM scientist would continue to be free to conduct their research using whatever model seems most appropriate. Nevertheless the availability of an ARM-supported model or suite of models would enable researchers with ideas but no models of their own to enter the modeling research arena.

We believe that ARM should consider supporting one or more SCMs, one or more CSMs, and perhaps one or more GCMs, on a facility basis, as outlined above. This need not be a huge undertaking;

18. GARP Atlantic Tropical Experiment; GARP is the Global Atmospheric Research Program.

several of the models could be and probably should be existing community models. An obvious example is the community SCM, based on the NCAR Community Climate Model (CCM), which is currently supported by NCAR and made available through the community via anonymous ftp. This community SCM could be adopted by ARM as a "facility" SCM. Similarly, the CCM itself could possibly be adopted by ARM as a "facility" GCM. In either case, no model development would be required on the part of ARM. Of course, ARM scientists are free to participate, along with the rest of the research community, in the further development of the CCM and the community SCM based on it, through the Atmospheric Model WG, which is a component of the NSF-sponsored Climate System Model framework.

7. From SCM technology to SCM science

7.1 Parameterization development and evaluation

The ARM SCM WG has focused, up to now, on what might be called the "technology" of SCM research. This is apparent in a brief summary of the steps we have followed to reach our current status:

- An observing system has been designed, implemented and improved.
- Data have been collected.
- Analysis methods have been designed, tested and improved.
- Modelers have been exposed to the data.
- Methods to force the models with data have been devised and tested and improved.
- Meanwhile, all along the way, new parameterizations have been developed (and are being developed), through the efforts of ARM scientists and others.

We are thus poised to enter a new phase of ARM SCM research, in which the SCM test, making use of ARM data (and other data, but especially ARM data), becomes a standard and accepted way of evaluating new parameterizations, at virtually all large-scale modeling centers (and centres).

The transition to this new phase is possible because parameterization development has been going on throughout the ARM Program (and even before ARM was initiated), by both ARM scientists and others. There is no need for the ARM SCM WG to agitate for or organize a parameterization development activity, simply because such research is already ongoing at a very high level. The SCM WG does need to make this research a focus of its future workshops and other activities. ***Henceforth, each SCM WG meeting will feature one or two extended discussions of specific new parameterizations and their performance in SCM tests (and other tests).*** We can also try to use our SCMs to investigate some cloud feedback issues, as suggested by Prof. J. Curry of the University of Colorado.

These changes are intended to shift the focus from the "technology" of SCM research to the science of parameterization development. Nevertheless, there will still be a need for improvements in data, in analysis techniques, and in forcing techniques.

7.2 Sensitive dependence on initial conditions, and statistical analysis of SCM results

Several SCM and CSM research teams have noted that their model results can be sensitive to the details of the initial conditions used. This is not surprising, because such sensitive dependence on initial conditions is a well-known property of nonlinear systems (Lorenz, 1963), and our models are certainly highly nonlinear. An implication of this finding is that we should be examining ensembles of simulations for a given case, rather than single simulations.

There is some evidence that CSMs are less sensitive to initial conditions that SCMs. This is disturbing, because in principle SCMs are supposed to give the same solutions as CSMs, for a given case. The exaggerated sensitivity of SCMs, if it is real, may arise from the "if tests" which can be found in most parameterizations. This suggests that the elimination of such tests and a reduction of the sensitivity of SCMs to their initial conditions should be a goal of future research on parameterization development.

With or without ensembles of simulations, strategies must be pursued for statistical analysis of SCM and CSM results. Such analyses might take the form of compositing according to the phase of the diurnal cycle phase, the stage of cloud system development, the dynamical sector of a cloud system, or correlations with various large-scale environmental parameters. Such compositing can filter out uninteresting random errors and expose physically important systematic errors.

In order to follow this approach, we need a sufficiently large sample. If a typical SCM IOP is 3 weeks in length, 6-7 IOPs in a given season might be required for a statistically significant sample. This is one of the important strengths of ARM's strategy of maintaining an extended presence in the field.

7.3 Analysis of additional weather regimes

There is a need to conduct and analyze SCM IOPs for additional climate regimes. Important examples include:

- tropical convection over land
- marine stratocumulus clouds
- storm tracks over the midlatitude oceans.

In order to obtain such data, ARM needs a mobile observing system. Cooperation with other field programs will also be very important.

7.4 Idealized test cases

The SCM WG plans to conduct idealized simulations with our SCMs and CSMs. In one simple example, all models will be run to equilibrium with identical forcing, using average summer and winter conditions for the ARM site. The simulated climates produced, and the length of time required for each model to reach statistical equilibrium will be investigated. GCSS also has an interest in this activity, which may be pursued collaboratively.

8. Summary and recommendations

SCM research is the key to tying ARM measurements to GCMs. ARM has assembled unique data sets suitable for driving SCMs. The SCM approach to the analysis of ARM data represents one key element of a multi-thrust research strategy, which also includes IRF research and global climate modeling.

The SCM WG has developed elaborate methods for the analysis of ARM data for use with our SCMs and CSMs. One of our most important current difficulties is analyzing the observed advective tendencies of condensed water variables. We need additional analyses from the Cloud WG and the IRF WG. These collaborative efforts are under way. In addition, we are working collaboratively with the international GCSS activities.

Up to now ARM SCM research has been conducted primarily with the SGP data. The location of the SGP site allows sampling of a broad spectrum of meteorological conditions, ranging from cold Canadian outbreaks to warm, humid subtropical Gulf air masses. Nonetheless, the climate regimes of the TWP and NSA/AAO allow the testing of more extreme environments for cloud formation and radiation interactions than we regularly see at the SGP. We hope to make use of data from one or more SCM IOPs at the TWP and NSA/AAO sites.

We recommend exploring the use of remote-sensing and associated retrieval of physical variables as a supplement to the radiosondes, with the potential of reducing the need for high-frequency release periods and extending the length of our SCM study periods. We will work with other parts of the ARM Program and Science Team that have expertise in characterizing the atmospheric state in the column over the ARM site from remotely-sensed data.

The SCM WG is embarking on a new phase of its activities, in which it will emphasize the in-depth analysis of major emerging parameterizations and their evaluation through the use of ARM data and other data. There will also be a continuing need to refine the techniques used in SCM research.

We recommend that ARM establish and/or strengthen its cooperative arrangements with existing operational NWP centers such as NCEP and ECMWF, in order to:

- ensure ongoing and close scrutiny of cloud and radiation forecasts for the ARM sites; and

- explore the use of assimilation products for forcing SCMs and CSMs.

Finally, we note that DOE's proposed Accelerated Climate Prediction Initiative (ACPI) is targeting climate simulations with 10-30 km resolutions. It is doubtful that many of the current GCM parameterizations will work adequately at that resolution. Hence, improved parameterizations will be needed. The focus of ARM is well suited to support this, with our data and SCM work. We need to be keenly aware of the objectives and tasks laid out for ACPI, and assist wherever possible.

Appendix 1

First SCM Workshop, April 29-30, 1996

A meeting on the Single Column Modeling (SCM) efforts of the ARM Program was held at LLNL on April 29-30 1996. The general purpose of the program was to foster communication and interaction among the members of the ARM community involved in SCM, in particular between the ARM Science Team and the ARM infrastructure. We attempted to communicate results of the various SCM efforts in the ARM community, and to assess the quality of the data products used to drive an SCM. Ultimately, we'd like to improve the quality of these data products. The format was standard for a workshop. Members of the ARM infrastructure reported on data products, data handling, quality assurance, and instrumentation at the ARM facility. Science team members presented results of their research efforts, with emphasis on using ARM data to drive SCM.

Infrastructure Reports

Marty Leach described the algorithm and data flow in an objective analysis used to create profiles of wind, temperature and moisture, the advective tendency of temperature and moisture, the wind divergence and the vertical velocity. A qualitative comparison of the fields with those from the Rapid Update Cycle (RUC) model was presented. There was lots of feedback and an action item (see below) list was developed for the next workshop.

Ric Cederwall presented an overview of instruments at the ARM site and the data streams available from those instruments. John Yio discussed Quality Assurance Issues and Dave Turner presented techniques to derive thermodynamic quantities from the AERI and MWR.

Science Team Reports

Single Column Models

Dave Randall, Colorado State University, presented results from the CSU SCM, using the LLNL objective analysis as initial conditions and boundary conditions. At CSU, they have compared model results from 4 SCM IOPs with mixed results. The most glaring problem is the inability to recover from poor initial conditions. This is most likely because the advective tendencies are not dependent on the mean profiles. It has been suggested that representing the forcing terms in flux divergence form may help.

Sam Iacobellis, Scripps Institute of Oceanography, presented the results of the Scripps SCM. The Scripps group use a 24 hour relaxation in their simulations, essentially nudging the model results with observations. They then compare the model results to 24 hour running means of the observations. The best results were the downwelling infrared radiation. Two different cloud physics schemes were used (Sundquist, and Smith) to compare column integrated liquid water content with the observed at the ARM site. The Sundquist scheme was apparently superior, at least for the limited data shown.

Steve Ghan, of PNNL, presented results from several models, an SCM, a regional model, and a GCM. Ghan's group is developing a stratiform cloud water parameterization scheme for a GCM. They had little success with the SCM, which they attribute to errors from the objective analysis.

Jonathan Petch of NCAR used a SCM version of the NCAR GCM. He made the point that neglecting cloud liquid water flux into the grid volume is a source of error for the SCM efforts.

Cumulus Ensemble Models

Steve Krueger of the University of Utah, and Kuan-Man Xu of Colorado State presented results from CSMs, using the large scale fields for the forcing, similar to driving an SCM. Both had problems however. Krueger's results were better without the large scale forcing. He was trying to simulate Altocumulus Ac) clouds and was successful in getting the Ac to grow from earlier cumulus at the top of the boundary layer when the large scale forcing was neglected. Krueger also had several suggestions for the objective analysis, recommending time filtering etc.

Xu showed results from the UCLA GCM and a CSM. In his CSM results, he used observed winds to nudge the results towards observations. Similar to Randall's results, there was a large temperature bias but with a small diurnal cycle. He attributed the too cool temperatures to too little subsidence in the model, pointing to errors in the divergence calculations. In the CSM calculations, he used a model that has performed well in the tropics. For the SGP site, the results were sensitive observed sensible and latent heat fluxes. The radiative heating rates were sensitive to the soil temperature and the precipitation rate was sensitive to the bulk cloud microphysics parameterization.

Mesoscale Parameterization

Two science team presentations involved using mesoscale models to develop parameterizations for the GCM. Hongli Jiang, working with Bill Cotton at CSU, presented results trying to incorporate mesoscale convective systems (MCS) in an SCM of GCM. The concept is based on sub-grid scale total kinetic energy (TKE) being partitioned into Cumulus Kinetic Energy (CKE) and Mesoscale Kinetic Energy (MKE). As CKE increases, there is a conversion into MKE. MKE is also produced through interaction with the large scale baroclinicity. The amount of MKE defines the existence of MCS. Questions remaining include the autoconversion rates of CKE into MKE, MKE dissipation, and threshold values of MKE for MCS existence.

Steve Chin of LLNL reported on his work developing an Anvil Cirrus Parameterization (ACP), showing results from a small scale cloud model in both two and three dimensions. He examined the dependence of anvil formation on both the large scale bulk Richardson number and the convective available potential energy. His tentative conclusions are that anvil formation depends on mesoscale ascent, which in turn depends on the wind profile and the jet structure. His work shows promise in mapping the mesoscale ascent on to the large scale through the bulk Richardson number.

Large Scale Models

Ferd Baer, University of Maryland, presented interesting results comparing radiative heating rates from GCM simulations using different radiative parameterizations. Not surprisingly, he found that the longwave heating rates and profiles are sensitive to clouds. He also concluded that the radiative forcing was more sensitive to the phase than the amplitude model disturbance. He concluded that the IR heating algorithm is important in the model output evolution, and that the heating rate depends on the model truncation or differencing algorithm. Also, the physics modules in codes may become biased and tuned to compensate for insufficient physics in other modules.

Other techniques for the forcing terms

In addition to the modeling efforts, several science team members are developing other methods for deriving the forcing terms for the SCM. Minghua Zhang of SUNY Stony Brook, presented a variational technique using conservation of water vapor as a constraint equation. Jean-Francois Louis, AER, also used a variational method to assimilate observational data, essentially a one-dimensional adjoint technique. The advantages of these techniques are the physical consistency of the data produced. The disadvantages are the complexity and the possibility of non-convergence.

Jimy Dudhia of NCAR presented a four dimensional data assimilation scheme, using the MM5 model with Newtonian nudging. Again, the advantage is the physical consistency of the data sets, as well as the spatial and temporal coverage. The disadvantages are the cost and the assimilated data will reflect the parameterization inherent in the model used (MM5 in this case).

Action Items

The action items for the ARM infrastructure group arising from the workshop are listed below in bullet form.

- Quantify Error of Data Analysis Products: Variability of local temperature change to advective tendency. Compare to NWP products, especially for divergence and omega.
- Improve Data Analysis: First guess from NWP or large scale analysis. Time filtering and time averaging. Other techniques (e.g. Variational).
- Establish Web Bulletin Board for SCM discussion.
- Agreed to use Oct. '95 and Apr. '96 IOP data sets for comparison at next SCM workshop (late '96).
- Provide written summary of this workshop.

Appendix 2

Second SCM Workshop

Executive Summary of Second SCM Workshop LLNL January 8-9, 1997

The focus of the Second SCM Workshop was on (1) progress in SCM and related studies, especially using ARM data, (2) adequacy of current ARM data streams and derived products for SCMs, and (3) recommendations for improvements in derived products and acquisition of new data streams. Over 30 participants attended. Details of the workshop will be available on the web soon.

Recommendations

1. Utilize variational analysis for deriving SCM forcing terms

ARM should explore other objective analysis techniques to provide required SCM forcing terms using ARM data. In particular, variational analysis schemes holds promise. This is a research effort that is beyond infrastructure resources. The SCM group recommends that the variational approach be given a high priority and views this as needing a Science Team level of effort, in collaboration with the ARM infrastructure. Objective analysis (which includes variational analysis) is an area of active research, and ARM is pushing objective analysis capabilities to the limit in deriving SCM forcing terms using ARM data. Some SCM group members have profitably used results from the variational analysis research of Minghua Zhang, SUNY Stony Brook, who has applied his techniques to ARM SCM IOP data.

2. Conduct an SCM Intercomparison

The ARM SCM effort has matured to the point that we are ready for an SCM Intercomparison. The Summer 1995 SCM IOP has been selected for the initial study. This IOP is desirable since it is a highly convective period. The Spring 1997 SCM IOP was identified as a candidate for intercomparison, and is attractive since it is concurrent with the Cloud Radar Validation IOP having two cloud radars and two aircraft providing cloud data. Further consideration will be given once the IOP is completed. Other candidates include Fall 1994 and Fall 1997 SCM IOPs. The Fall 1997 IOP deserves consideration since it will occur with the Cloud/Aerosol, Shortwave Radiation, Water Vapor, and ARM-UAV IOPs, which will provide a wealth of cloud, aerosol, water vapor and radiation data for use in the SCM Intercomparison. Steve Krueger will pursue having the GEWEX Cloud Modeling Group consider an intercomparison of their cloud models during one or more of the SCM IOPs selected for the intercomparison study. This GEWEX group has been planning to do an intercomparison over land, and the ARM data set is well suited to their needs. The cloud modeling results will be of benefit to the SCM Intercomparison. Steve Krueger has led a model intercomparison before, and will provide guidance for the SCM Intercomparison.

3. Establish an easier way to view and obtain SCM data from ARM

LLNL has developed an SCM web page for viewing SCM data sets. However, ARM currently delivers data through the Experiment Center and the ARM Archive. LLNL will establish a capability to initiate the delivery of SCM data sets from the SCM web page, using existing ARM data delivery paths.

CSU currently maintains an SCM web page that includes graphical summaries of SCM IOP data sets and an ftp option for users to obtain these data. CSU will continue this capability in the short-term, but will discontinue this role once the ARM infrastructure has a similar capability.

Action items

1. Compile a summary report of the workshop (LLNL: Leach, Cederwall)

2. Layout procedures for SCM Intercomparison, and develop draft of model input/output lists, and data validation, as well as prescription of Summer 1995 case study, for discussion at ARM Science Team Meeting breakout session. (Krueger, Cederwall)

3. Perform variational analysis for Summer 1995 SCM IOP to be used in SCM Intercomparison (SUNY SB: Zhang)

4. Develop a time-filtering extension to the current objective analysis scheme (LLNL: Leach, Yio)

5. Develop cloud products for use with SCMs (Cloud WG: Krueger, Rodriguez)

6. Analyze ECMWF data and compare with RUC data and objective analysis (LLNL: Leach, Yio)

7. Continue development of infrastructure SCM web page and pursue options for a ‘one-stop’ data delivery of SCM data via the web (LLNL: Yio, Cederwall)

Appendix 3

Breakout Session at 1997 ARM Science Team Meeting

Input Datasets

1. Which objective analysis versions to use? Open issue. Possibilities:

   version A: original with sondes and profilers only

   version B: version A with RUC data around the outer apron

   version C: version A with time filtering

   version D: version B with time filtering version E: variational analysis (Minghua Zhang)

   others?

2. How to calculate/provide upstream values needed by 'relaxation' forcing? Available now in objective analysis data streams. LLNL will send out documentation soon to close this issue.

3. Is the vertical velocity needed at the surface? Yes.

4. Include surface pressure tendency in the input file? Yes.

5. Need surface roughness, albedo, emissivity?

   albedo needed -- get from NASA Langley (Charlock, Whitlock, Minnis)

   surface roughness -- just set to 10 cm?

   emissivity -- just set to 1?

6. Where will files be made available (and documentation)? LLNL will serve as repository, probably via ftp.

Output Datasets

1. Output time intervals: hourly.

2. What results to submit? Open issue. See Section 3 of draft as starting point.

3. Where to submit results? LLNL.

4. Deadline for submitting results? Open issue. probably during summer; may be iterative for first pass. Substantive results to be submitted and displayed by SCM Workshop in September

5. Who will compile the results? LLNL. will use procedures and plotting utilities available from Steve Krueger (developed for previous GCSS WG4 intercomparison).

Appendix 4

Third SCM Workshop

Summary of the Third SCM Workshop Lawrence LLNL January 7-8, 1998

The focus of the Third Single-Column Model (SCM) Workshop was (1) progress on the SCM Intercomparison study and further efforts needed, (2) adequacy of current ARM data streams and methods for deriving data streams for SCMs, and (3) recommendations for improvements in derived products and acquisition of new data streams, especially from remote sensing. Below is a summary of the workshop proceedings, including recommendations, action items (with assignments and completion dates), session summaries, and list of the 29 attendees.

Recommendations

1. FY1998 and FY1999 SCM IOPs

The second SCM IOP in FY1998 should be coincident with the Cloud Physics IOP, tentatively planned for May 1998. We recommend that there be three SCM IOPs scheduled for FY1999. One should be in the winter season to repeat the Winter 1998 SCM IOP and give a second sampling of cold, synoptically-driven conditions. The second FY1999 SCM IOP should follow shortly (say in March) to capture cool season, stratus conditions. The third SCM IOP should sample local convection without strong synoptic forcing; summer into early fall is preferable. Scheduling with other IOPs is desirable, especially those collecting cloud and radiation data in the column. We seek to have one or two IOPs in FY1999 that occur when the AERIs are installed at the Boundary Facilities. Such IOPs allow the testing of derived SCM data streams that depend on input data from remote sensing rather than radiosondes. We will make comparisons over scenarios with systematically fewer sondes used in the analyses to quantify the impact on SCM results (see Recommendation #3).

2. Variational Analysis as Primary Method for Deriving SCM Input Data Streams

Initial analysis of simulations in the SCM Intercomparison confirms that the SCM forcing terms obtained from variational analysis are superior to those from the Barnes objective analysis. It is recommended that variational analysis become the primary method for deriving SCM forcing terms from ARM data. The data processing and analysis procedures developed by Minghua Zhang should be merged with those developed at LLNL to create an operational system that can be applied to ARM data sets by the ARM infrastructure. Since the SCM depends critically on the forcing terms derived from ARM data and the techniques for doing this are still an active area of research, we recommend an active collaboration between Minghua Zhang and the LLNL infrastructure to ensure that state-of-the-science techniques are used for supporting the SCM research area.

3. SGP Site-Wide Atmospheric State Characterized by Remote Sensing

The forcing terms to drive SCMs depend on observations, whether the Barnes objective analysis or the variational analysis method is used in the derivation. To date, these observations have been primarily from radiosondes and, due to the costs, limited to seasonal IOPs. To the degree possible, the SCM WG is interested in exploring alternatives based on remote sensing to obtain profiles of the atmospheric state in the column over the ARM site that we now obtain from radiosondes. Development of retrieval algorithms for temperature, water vapor, and winds from remote sensing has been an ongoing effort in ARM. The SCM WG would like to benefit from that effort. However, most of the remote sensing is concentrated at the Central Facility. The spatial gradients of atmospheric state quantities are essential for developing estimates of advective tendencies. Once remote sensing can capture these spatial gradients, it is reasonable to develop SCM forcing terms from quantities retrieved from remote sensing, and compare these with forcing terms derived from the data streams currently used. We propose to collaborate with other groups in ARM, especially the Atmospheric State Steering Committee in the IRF WG, by making our requirements clear, and undertaking systematic comparisons to evaluate the adequacy of approaches that depend on reduced ARM radiosondes. We are looking to other parts of the ARM Program to provide the best estimate of the atmospheric state across the SGP site from which we can obtain our needed forcing terms.

4. Cloud Properties Needed for SCMs

Initial analysis of the SCM Intercomparison highlights the impact of clouds on the results. During clear sky conditions during the test period, SCMs performed better than during cloudy conditions. The cloud-resolving model did better at handling the cloudy conditions, but at the expense of large computer times per run. Basic cloud characterization across the SGP site is needed to estimate cloud fraction as a function of height and time. The millimeter cloud radar, and associated cloud products, provides great detail at the Central Facility. Satellite products provide a less well-resolved estimate across the whole site. We look to the Cloud WG to provide their best estimate of macrophysical cloud characterization across the SGP site. Additional cloud properties desired include cloud boundaries, cloud overlap, particle size, cloud droplet and cloud ice number concentration, cloud optical thickness, and horizontal advective tendencies of liquid water and ice.

5. Cropland Surface Flux Observations Needed for SCM Surface Forcing

Initial analysis of the SCM Intercomparison points out the need to better characterize surface flux at the SGP site, particularly over cropland. The current surface flux data set is predominantly from the Energy Balance Bowen Ratio (EBBR) stations, which sample undisturbed areas such as pastures and rangeland. The croplands are sampled by the Eddy Correlation (ECOR) stations. The ECOR systems have produced much less data due to instrument system reliability problems, which are inherent in this research level system. Nonetheless, the data sets expected from the ECOR systems are of high priority for SCM surface forcing, where they are used in (i) direct fusion of the point observations into site-wide values of surface flux, and (ii) validating the SiB2 model-based flux estimates provided by Chris Doran. It is clear from the averaged summer values for EBBR that we are missing the hotter, drier surface conditions on clear days over the harvested wheat fields concentrated in the central north-south band of the SGP site. We recommend that increased attention be given to obtaining the critical cropland surface flux measurements.

Action Items

1. Complete analysis of Case 1 of the SCM Intercomparison, prepare a paper for publication (Cederwall, Yio, Intercomparison participants) September 1998

2. Prepare data streams for Case 2 of the SCM Intercomparison (Summer 1997 SCM IOP) to be conducted in conjunction with GEWEX GCSS WG4 (Cederwall, Yio, Krueger) July 1998

3. Prepare data streams for the Fall 1997 SCM IOP (Case 3?) to permit SCM comparisons with the other Fall 1997 IOPs, especially the Cloud, Water Vapor, and UAV IOPs (Cederwall, Yio) December 1998

4. Provide GOES satellite loops to document conditions during selected SCM IOPs (infrastructure, Krueger) June 1998

5. Provide estimates of PBL depth during selected SCM IOPs (infrastructure, Coulter) July 1998

6. Investigate SCM sensitivity to surface forcing for Case 1 (Intercomparison participants) May 1998

7. Develop an interactive analysis capability for the SCM Intercomparison web page, for user specified data plotting and retrieval (Yio) August 1998

8. Prepare a white paper on ARM SCM requirements for guiding efforts to meet those requirements by remote sensing (Randall, Somerville, Krueger, Cederwall) July 1998

9. Prepare a white paper on the future direction of the ARM SCM effort (Randall, Cederwall) June 1998

10. Report status of SCM WG activities to IRF WG (Cederwall) January 1998 -- done

Summary of Sessions

1. SCM Intercomparison -- Overview and Preliminary Results

Ric Cederwall gave an overview of the SCM Intercomparison study, outlining the procedures, data sets, and participants. Three methods of prescribing advective forcing were tested: (1) observed total advective tendency, (2) observed horizontal advective tendency plus vertical advective tendency estimated using observed large-scale vertical motion and the model-predicted vertical gradient, and (3) horizontal advective tendency estimated using a relaxation toward upstream values, plus vertical advective tendency estimated as in (2). SCM advective tendency terms were obtained in two ways: (a) Barnes objective analysis using ARM sounding and NOAA wind profiler data, and (b) variational analysis (provided by Zhang) that uses additional data to adjust the advective tendencies in order to match the observed column-integrated tendencies of mass, moisture, static energy, and momentum (Zhang and Lin, 1997). Surface forcing was prescribed from two methods of heat and moisture flux estimates: (i) area-averaged observations from Energy Balance Bowen Ratio (EBBR) stations, and (ii) area-averaged SiB2 model output (from a 6.25-km grid) by Doran's ARM project that uses ARM observations as input. The case study period was from the Summer 1995 SCM IOP (7/18/95-8/3/95).

Minghua Zhang gave background on the variational analyses that he provided for the study. Ric Cederwall then presented the results received to date. Active discussion followed. As anticipated, the CSM of Xu performed better than the six SCMs. The SCMs agreed better with observations in clear sky conditions, as anticipated. There was significant overprediction of temperature in the lower portion of the column during the first part of the simulation.

2. SCM Intercomparison -- Presentations by Participants

Dave Randall (CSU), Sam Iacobellis (Scripps/UCSD, with Richard Somerville), Steve Ghan (PNNL), Ulrike Lohmann (Dalhousie), Steve Klein (NOAA/GFDL), Shaocheng Xie (SUNY Stony Brook, with Minghua Zhang), Xu (CSU).

3. SCM Intercomparison -- Discussion of Advective Forcing and Surface Forcing

For testing parameterizations, such as cloud parameterizations, the relaxation method for advective tendency is preferable, since the atmospheric state is not allowed to drift away from observations. The observed total advective tendency (option 1 above) allowed the least model adjustment to external forcing, while option 2 allowed the SCM to respond to the predicted profiles via the vertical advection term. An alternative that allows interesting diagnostic possibilities (presented by Lohmann) was the use of option 3 (relaxation) for temperature only, and options 1 or 2 for moisture, so that the SCM could predict the moisture profile for given temperature conditions.

Prescription of surface flux is perhaps an overly constraining forcing that decouples the model from the surface, since predicted temperature and moisture at the lowest level in the model is not coupled to the surface forcing. Alternatives are either to prescribe a 'skin' temperature and moisture that is consistent with the estimates surface flux, given the predicted temperature and moisture at the lowest model level, or use a strong relaxation to observed conditions at the ground. In considering alternatives, it was clear that estimates of boundary layer depth are needed.

4. Joint Study with GEWEX GCSS WG4 (and WG1)

Steve Krueger gave an overview of current activities of the GEWEX Cloud System Study WG 4 (deep convection). He presented results of their latest intercomparison study. This WG is interested in performing an intercomparison for a mid-latitude, continental case, and the ARM SGP site is an excellent location. The Summer 1997 SCM IOP data set appears to be well-suited for their needs, and provides ARM with a potentially fruitful collaboration. The detailed cloud modeling and analysis available to ARM from GCSS WG4 would be highly beneficial for testing and evaluating of SCM cloud parameterizations. GCSS WG 1 (shallow clouds) would be interested in data sets for cool season stratus conditions at the SGP site. The collaboration will be pursued more fully during the Summer 1998 meeting the GCSS WGs.

5. Adequacy of ARM data

To date, the SCM IOPs have provided good sampling of warm season conditions at the SGP site, when local convection plays a more important role that synoptic forcing. During those IOPs, we have also captured some synoptic events, however we have had no characterization of the cold season or of the cool season. The Winter 1998 SCM IOP will help characterize the cold season. Another cold season SCM IOP and a cool season SCM IOP will gave us a more complete sampling. Overall, the strong convection conditions remain those most challenging for the SCMs, and therefore a major portion of the SCM IOPs should occur under those conditions.

The SCM IOP has been the primary source of data for SCM forcing. The WG recognizes the value of moving toward remote sensing as a means of obtaining data for SCM forcing. This would allow SCM experiments to be conducted over continuous periods, rather just IOPs, and hence increase the realizations for ensemble studies. Also, the necessity for operating in IOP mode is due to the cost of high frequency soundings. Reducing the dependence on the high-frequency soundings will represent a savings for the ARM Program. Once the AERIs are installed at the Boundary Facilities (early to mid FY1999), the SCM WG will undertake comparisons with forcing data derived in the current manner with the full complement of sondes, and with forcing data using fewer and fewer sondes to evaluate the impact of various sampling scenarios. The group will also prepare documentation on the time and space resolution needed for SCM. We need active participation by other parts of the ARM Program that are involved in retrievals of atmospheric state variables from remote sensing, especially the Atmospheric State Steering Committee in the IRF WG.

6. Future directions

The WG considered the future direction of its work in the context of a question posed by Gerry Stokes "What would a meaningful SCM result look like?" Dave Randall offered an answer in terms of the role of SCMs in a well-rounded research strategy. Practically speaking for ARM, a useful result would be that a promising new parameterization is tested in an SCM using ARM data, and then is adopted for use in a climate model. The SCMs play a valuable role in the critical stage of parameterization development when various ideas are being formulated and tested, where particular processes can be isolated. Richard Somerville pointed out the important results that SCMs with ARM data provide to falsify hypotheses that have been assumed in previous, commonly-used parameterizations. An example of this is the relation between relative humidity and cloud fraction. SCMs allow the testing of prognostic cloud water schemes that can represent more realistic cloud radiative properties. Tony Del Genio presented the characteristics of a useful SCM result, in more general terms, that encompassed what Dave Randall said in terms of a practical result for ARM. Tony also included the statistical context of the result, where case studies may be suggestive, but ensemble statistics a more powerful evaluation of parameterizations.

7. Wrap up

Action items were developed, based on discussions during the workshop, along with assignments and timelines. The path forward on publishing a paper on Case 1 of the SCM Intercomparison study was discussed briefly; further discussion will be held at the SCM breakout session at the ARM Science Team Meeting. Other topics for the agenda of that breakout session were identified. The WG discussed future interactions with the IRF WG, and what should be reported at their upcoming meeting later in January. Finally, we considered the focus and timing of the next SCM Workshop. Testing of radiation parameterizations is one focus area. Another is cloud parameterizations, especially in light of the collaboration with the GEWEX cloud study WG on Case 2 of the SCM Intercomparison. It would be beneficial to move the workshop earlier in the year so that there was more time between the workshop and the Science Team Meeting. Late October or early November is a candidate time. LLNL has been a good location, given its facilities and ease for the infrastructure in hosting the workshop. However, other locations may facilitate interaction with some members of the IRF group involved in radiation parameterizations.

Workshop Attendees

ARM Science Team: Dave Randall (CSU, SCM WG Chair); Doug Cripe (CSU), Tony Del Genio (NASA/GISS), Chris Doran (PNNL), Shelby Frisch (CSU/CIRA), Steve Ghan (PNNL), Jim Hack (NCAR) Sam Iacobellis (UCSD/Scripps), Steve Krueger (University of Utah, Cloud WG Co-Chair), Richard Somerville (UCSD/Scripps), Shaocheng Xie (SUNY - Stony Brook), Kuan-Man Xu (CSU), Minghua Zhang (SUNY - Stony Brook).

ARM Technical Infrastructure and Management: Ric Cederwall (LLNL, Infrastructure SCM Liaison), Steve Chin (LLNL), Ted Cress (PNNL, ARM Technical Director), Pat Crowley (DOE, ARM Scientific Director), Mark Miller (BNL), Michael Splitt (University of Utah), Dan Rodriguez (LLNL, Infrastructure Cloud Liaison), John Vitko (SNNL - CA), John Yio (LLNL), Bernie Zak (SNNL - NM, NSA/AAO Site Program Manager).

Visitors: Jerry Harrington (University of Alaska - Fairbanks), Yanping He (University of Arizona), Steve Klein (NOAA/GFDL), Ulrike Lohmann (Dalhousie University), Rawlings Miller (University of Arizona), Jerry Potter (LLNL/PCMDI).

Appendix 5

SCM Breakout Session at March 1998 ARM Science Team Meeting

The main topic of the breakout session was the status of the SCM Intercomparison. Ric Cederwall gave an update on the results of the revised runs, using the Doran SiB2-based surface fluxes. Most results showed slightly higher temperature bias and slightly lower moisture bias -- the expected response to higher sensible and lower latent heat fluxes during clear-sky daytime conditions that prevailed during the middle of the IOP. The results submitted by Sam Iacobellis showed an interesting response. especially for temperature. He found the increased temperature bias in the lower levels of the model, but a marked decrease in temperature bias (an improvement) above 850 mb. Similar, but less dramatic, tendencies were found for moisture. Sam is investigating the reasons for this. Intercomparison participants also gave briefs reports on their recent results. Georgiy Stenchikov (Univ. of Maryland), a new participant in the intercomparison along with Alan Robock (Rutgers), gave a brief overview of SCM work they are doing related to ARM. They are investigating the influence of different land-surface models on large-scale simulations, and also studying the response of the diurnal cycle to potential climate changes. Dave Randall concluded this part of the breakout session with a discussion of the proposed paper on Case 1 of the SCM Intercomparison. The sections of the paper were outlined, with writing assignments. Preliminary input is requested by June 1st, with the paper competed by the end of summer. Several supporting papers (already published or planned to be submitted) were identified.

The next part of the session focused on future cases for the SCM Intercomparison. The next case will focus on cloud parameterizations, in collaboration with the GEWEX Cloud Study system WG 4 (Deep Convection), chaired by Steve Krueger. Steve gave a summary of the objectives and previous results of this group. We will use the 1997 Summer SCM IOP (6/18 - 7/18) for this case study. There is a meeting in Boulder on July 14, 1998, where we will discuss this among the GEWEX investigators; Ric Cederwall will attend, at the invitation of Steve Krueger, to present the ARM data and analyses available for that period. Ric, John Yio, and Minghua Zhang will try to have the variational analyses done by that time. Another case study beyond that is the Fall 1997 Integrated IOP. The focus here would be on radiation parameterizations, in collaboration with the IRF group, using data from the UAV and Shortwave IOPs, as well as the Cloud and SCM IOPs.

The next topic was SCM exercises at the TWP and NSA/AAO sites. We asked Chris Fairall to join us and discuss the Nauru99 campaign and its potential as an SCM IOP. The triangular arrangement of Nauru and two research vessels, with about 200 km legs for 5-7 days, is our best opportunity for an SCM exercise there. We will study the proposed instrument list further to evaluate how well we can obtain SCM forcing terms and validation data sets. We also discussed an SCM IOP at the NSA/AAO site. The spring-summer melt season is the best time. Jim Pinto indicated Judy Curry's interest in having a collection of aerosondes (remote-piloted vehicles with sonde-type instrument packages) fielded to document the column. More work is needed to layout the hypotheses to be tested and the optimal sampling strategy. SCM exercises in both locations will make use of the ECMWF data sets that ARM is receiving routinely.

Martin Miller discussed with us the use of ECMWF analyses in our SCM work. This was a follow-on to his plenary talk earlier. There is much we can do here, including using the DDH output in our variational analyses. As we consider this further, we need to identify gaps that ECMWF could potentially fill with modified analyses. They are open to collaboration with us; Christian Jakob is planning to participate in the intercomparison.

Steve Krueger briefly reviewed the cloud products that the ARM Cloud WG is developing in support of SCM. These efforts are much appreciated, and the ARM project of Jay Mace is seen as a valuable source for these products. Estimates of site-wide cloud fraction and condensate advection are still the most difficult data products to obtain.

We briefly discussed the date and location of the next SCM Workshop. We settled on the week of October 12-16, 1998, in the San Francisco Bay Area as our target. The Cloud WG is considering a meeting at about the same time, and would like to overlap with the SCM Workshop for about a day. The IRF Group would like to have their meeting in the fall rather than January (to be offset from the annual Science Team by about 6 months). They have expressed interest in having a day or so of overlap with the SCM Workshop. Ric Cederwall will check on the availability of suitable facilities for such an integrated set of WG meetings, and keep the Cloud and IRF groups informed.

Attendees

Dave Randall (CSU), Ric Cederwall (LLNL), Martin Miller (ECMWF), KuanMan Xu (CSU), Doug Cripe (CSU), Steve Ghan (PNNL), Chris Doran (PNNL), Jim Hack (NCAR), Dave Parsons (NCAR), Jimy Dudhia (NCAR), Steve Krueger (University of Utah), Steve Lazarus (University of Utah), Jim Pinto (University of Colorado), Alan Robock (Rutgers), Georgiy Stenchikov (University of Maryland), Richard Somerville (Scripps/UCSD), Sam Iacobellis (Scripps/UCSD), Dana Lane (Scripps/UCSD), John Yio (LLNL), Jerry Potter (LLNL), Lazaros Oreopoulos (NASA/GSFC), Tony Del Genio (NASA/GISS), Wayne Feltz (University of Wisconsin), Eugene Clothiaux (Penn State), Chris Fairall (NOAA/ETL).

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